# MBE-IX: Ninth International Conference on Molecular Beam Epitaxy

**August 5-9, 1996**

**Mohamed Henini**

*The meeting was held in the beautiful campus of Pepperdine University situated in Malibu. I am told that Malibu's first residents, the native American Chumash Indians, named the stretch of beach at the mouth of Malibu Creek "Humaliwo" — or "the surf sounds loudly". Recreational opportunities abound for the water enthusiast here.*

The meeting was well attended with over 430 delegates coming from as far away as Japan, Europe, China, Australia, Mexico, Taiwan, Hong Kong, Korea and Singapore and, of course, a large contingent of our American friends. It was not just the famous beaches and surfing that attracted so many to this famous town on the West Coast of the USA. It was clear from the number of papers that the scale of effort on MBE is many times that of twenty years ago. There were 6 plenary speakers, 7 other invited speakers, 94 contributed papers and around 140 posters. These statistics were taken from the original list and the abstract book. Not all may have attended. In addition to the scientific presentations, a comprehensive four-day exhibition was included in the program with many participants from the manufacturers of MBE and related equipments. The conference attracted 33 commercial exhibits (vendors) and was supported by 8 sponsors.

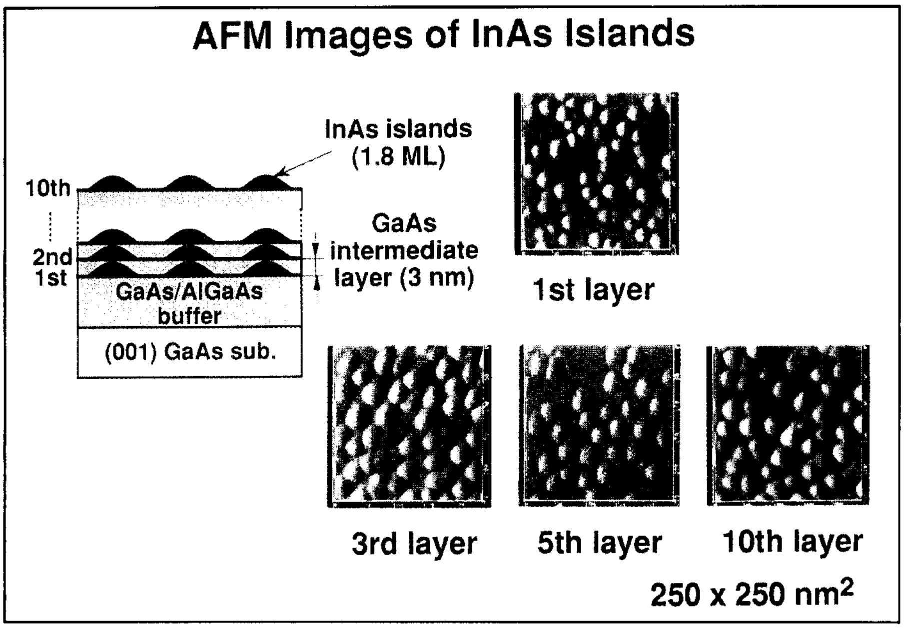


Figure 1: AFM images of stacked InAs islands with 3 nm GaAs intermediate layers (courtesy of Dr. Y. Nakata, Fujitsu Labs., Atsugi, Japan).

| | Invited Papers Papers | Contributed Papers | Posters | Total of Papers | Participant |
|---|---|---|---|---|---|
| USA | 8 | 39 | 44 | 91 | 248 |
| Japan | 4 | 24 | 32 | 60 | 64 |
| Germany | 2 | 14 | 16 | 32 | 33 |
| UK | | 4 | 16 | 20 | 14 |
| France | | 2 | 12 | 7 | 5 |
| China | | | 6 | 6 | 8 |
| Rest of World | 1 | 8 | 24 | 33 | 53 |

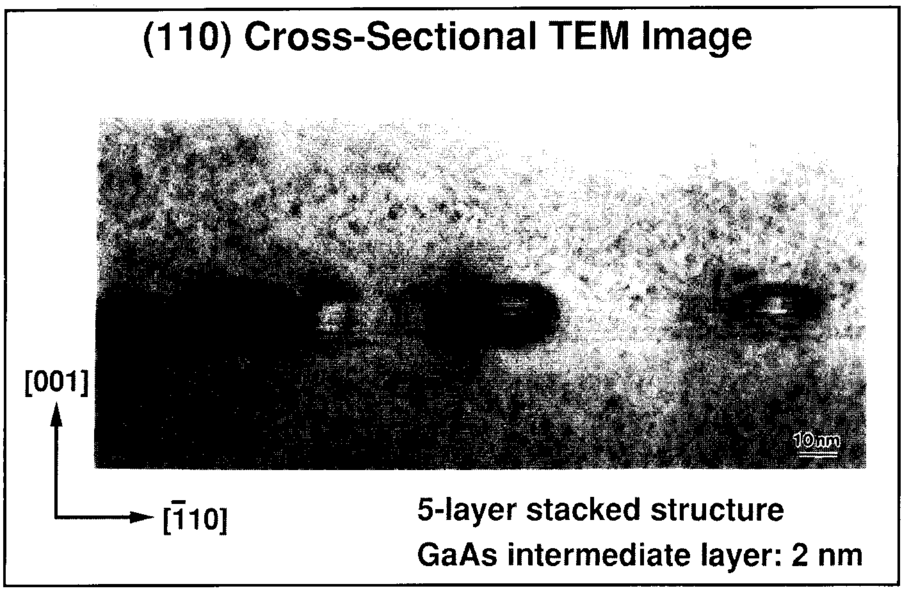


Figure 2: TEM image of the cross-section obtained from 5 stacked InAs island layers grown with 2 nm GaAs intermediate layer (courtesy of Dr. Y. Nakata, Fujitsu Labs., Atsugi, Japan).

The sessions were dedicated to:

1. Applications and future directions of MBE material
2. Nitrides
3. Quantum Dots
4. III-V growth
5. II-VI materials
6. III-V materials
7. Group IV materials
8. Regrowth
9. Sb and other materials
10. In-situ characterization and control
11. Laser growth
12. VCSEL growth
13. Devices and quantum wires
14. Lasers and detectors.

The following speakers were invited for the different sessions:

1. "Ground-based and space applications of MBE grown microwave devices" – J.V. DiLorenzo (Raytheon Advanced Device Center, USA).
2. "Millimetre wave and digital applications of InP-based MBE-grown HEMTs and HBTs" – P. Greiling (Hughes Research Labs., USA).
3. "MBE-based commercial HBT products" – B.V. Buskirk (TRW, USA).
4. "Mass production of InAs Hall elements by MBE" – I. Shibasaki (Asahi Chemical Industry Co. Ltd., Japan).
5. "Quantum cascade lasers operating with high power above room temperature" – J. Faist (Bell Labs, USA).
6. "Progress and prospects of Group III-nitride semiconductors" – I. Akasaki and H. Amano (Meizo University, Japan).
7. "Low-threshold (100 A/cm$^2$) injection lasers based on vertically coupled InGaAs/GaAs quantum dots" – V.M. Ustinov (Russian Academy of Sciences, St Petersburg, Russia).
8. "Surface chemistry during MOMBE studied by pulsed molecular beam" – M. Sasaki and S. Yoshida (Optoelectronics Labs., Japan).
9. "The fabrication of II-VI light emitting devices based on Be-compounds" – F. Fisher et al (Physikalisches Institut, Germany).
10. "MBE with solid phosphorus and arsenic valved cracking cells" – J.N. Baillargeon and A.Y. Cho (Bell Labs., USA).
11. "Fabrication and band alignment of pseudomorphic SiC, SiGeC and coupled SiC/SiGeC quantum well structures on Si substrates" – K. Brunner et al. (Max-Planck Institut, Germany).
12. "MBE growth of high power InAsSb/InAlSb quantum-well diode lasers emitting at 3.5 μm" – G.W. Turner et al. (MIT, USA).
13. "Integrated multi-sensor control of III-V MBE" – J.A. Roth (Hughes Research Labs., USA).
14. "In-situ observation of MEE GaAs growth using scanning electron microscopy" – Y. Homma et al. (NTT, Japan).
15. "MBE growth of highly reproducible VCSELs" – Y.M. Houng and M.R.T. Tan (Hewlett-Packard, USA).

Due to the size and scope of the conference, it is impossible to report on every aspect. I will therefore concentrate on those areas close to my recent research, namely, quantum dots. I have also selected some highlights of some of the invited talks.

## Invited talks

In the last decade Pseudomorphic High Electron Mobility Transistors (PHEMTs) have gone from a laboratory curiosity with unique low noise performance to a high volume commercial product for a variety of power and low noise applications. Technological advances in PHEMT fabrication – delta doping from both sides of the channel for high carrier densities, short gate length T gates for high transconductance, with double recesses for high breakdown voltage – have made PHEMTs suitable for power applications. The resulting high power along with high efficiency and linearity have allowed PHEMTs to be employed in a wide variety of applications. J.V. DiLorenzo (Raytheon, USA) described the variety of programs at Raytheon using PHEMT circuits. Military programs make use of PHEMTs for high efficiency power amplifiers and low noise receivers at X-band (Advanced Ground Based Radar), C-band (Navy Cooperative Engagement Capability), and Q-band (Milstar Satellite terminals such as Smart T). Space applications include a variety of commercial consumer satellite communications system components for such systems as Globalstar$^{TM}$, IRIDIUM, Inmarsat, and Odyssey operating at L and S band. There are also commercial applications consisting of high frequency converters, transceivers, and power amplifiers at L and S bands for personal communications products and cellular telephones. The challenges to produce very large quantities PHEMT wafers having precisely defined material structure were also discussed.

P. Greiling (Hughes Research Labs, USA) gave an excellent review on the millimeter wave and digital applications of InP-based MBE grown HEMTs and HBTs. The topics he discussed are summarised in the following paragraphs.

The growth of semiconductor device layers by MBE has allowed designers to develop a range of bandgap engineered devices including: 1) low noise HEMTs; 2) high power and power added efficiency HEMTs and HBTs; and 3) high speed digital/analog HBT ICs with an order of magnitude performance improvement over standard Si CMOS, Si bipolar transistors or GaAs MESFETs. The superior performance of MBE-grown, heterojunction devices has motivated the analysis, development, and optimization of Si, GaAs and InP-based HBT and HEMT technologies for military systems such as radar, communications, EW, as well as smart munitions. The transition of these technologies into commercial applications, however, is dependent on a rather different set of criteria than those for military applications.

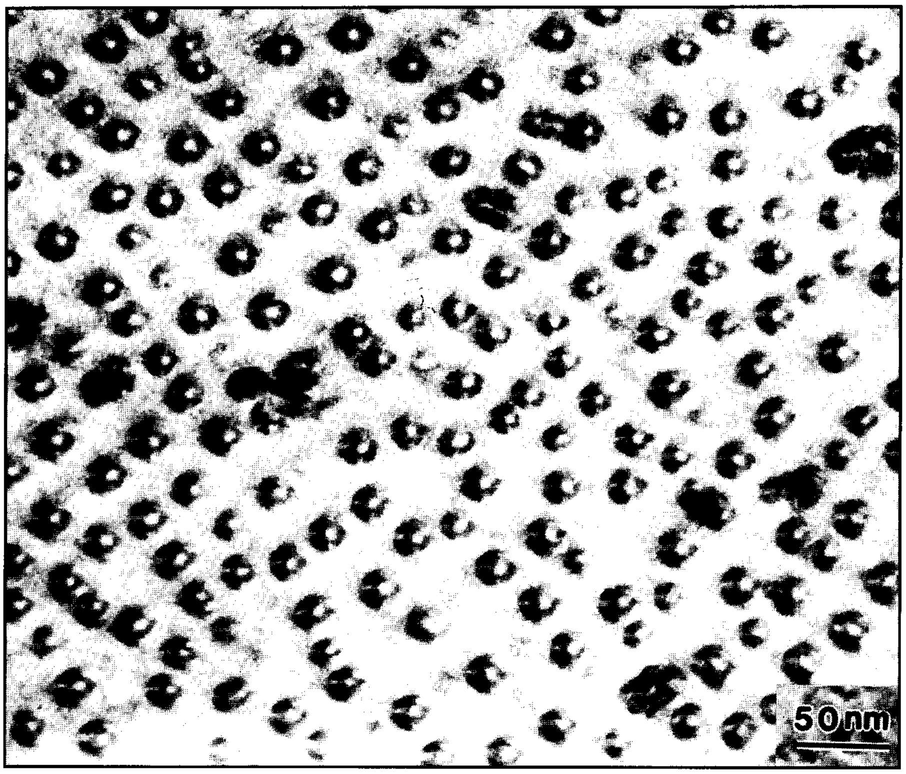


Figure 3: A plan view of a TEM image obtained from a 5-stack island structure grown at 2 nm intervals. The density of the islands is $8x10^{10}$ $cm^{-2}$. The authors state that this agrees well with the AFM results. Fluctuations in the lateral size of the islands seemed to be smaller than those in a single island layer and islands seemed to be ordered (courtesy of Dr. Y. Nakata, Fujitsu Labs., Atsugi, Japan).

MBE-grown heterojunction devices offer significant advantages in speed and frequency range of operations. Si bipolar ICs offer a 25 GHz device technology, for example, with practical operation at frequencies up to 5 GHz. Half-micron gate length GaAs MESFETs represent a 40 GHz technology, with effective operation at up to 20 GHz. In sharp contrast, MBE-grown heterojunction devices currently being developed (eg., SiGe-, GaAs-, and InP-based HBTs, and GaAs- and InP-based HEMTs) offer over 100 GHz device technologies, with operation extending well into the millimeter wave frequency range.

The enhanced performance of these MBE-grown heterojunction device technologies will help meet the requirements of future military systems. In particular, the next generation of phased-array radar systems will require reduced weight and volume as well as enhanced power/efficiency performance parameters to fulfill military needs. System operating frequencies will extend from the ultra-high frequency (UHF) range up through the microwave and millimeter wave frequency regimes. The GaAs MESFET technology, which has evolved rapidly over the past several years, is approaching its perceived ultimate performance limits and is therefore unlikely to meet these advanced radar performance requirements. As a result, heterojunction device technologies are being developed in order to produce T/R modules with octave bandwidths, noise figures (NF) under 2 dB, output power of 20 W and power added efficiencies (PAE) greater than 30%. These improved radar system will offer improved power-aperture products, broader bandwidths, reduced prime power consumption, and enhanced reliability.

There is also a growing need for MBE-grown heterojunction devices to meet the performance requirements of current and future satellite communication systems, which are also moving to higher frequencies for increased bandwidth. For satellite communications, device performance, (ie, noise figure, power added efficiency and reliability), is all-important, and cost is not as critical an issue. Systems are being developed requiring devices operating from X through V band. These systems require low noise devices with less than 0.3 dB NF at X band, rising with frequency to less than 1 dB NF at V-band. Solid State Power Amplifiers (SSPAs) with 20 W and 40% PAE at Ku band and 1 W and 30% PAE at V-band are also needed. With the exploding market for data/voice/video communication, future satellites will also require on-board, high performance signal processing with 40 GBPS or greater capacity. Devices for satellite applications must also have a MTTF of greater than $10^7$ hr. at operating temperature. These performance requirements are helping expand the envelope of performance for MBE grown heterojunction device technologies.

For both radar and satellite systems as well as EW applications, designers want to digitize the signal as close to the front end as possible. This is driving the development of a 100 GHz or greater IC technology for A/D converters, synthesizers, MUX/DEMUXs, DDSs and PRNs. Requirements for A/D converters with 16 bits @ 100-200 MHz and up to 10-12 bits @ 10 GHz are appearing for advanced radar and EW systems. Synthesizers and DDSs operating in the 5GHz to 20 GHz frequency range are being designed for the next generation of satellite systems. These needs are encouraging the development of an MBE-grown heterojunction IC technology with fT and fMAX well above 100 GHz and a speed-power product in the range of 10 to 30 femtojoules.

For military systems the emphasis has almost always been on the enhanced performance of MBE-grown heterojunction devices and ICs. Cost of production has always played a secondary role, if it has been considered at all. Today, performance at an affordable cost, utilizing a dual-use industrial base, governs both R&D investment and procurement. In the future, the cost-driven, commercial markets of automotive collision warning radar, personnel communication systems, and digital radios will determine the direction of device and IC R&D investment. Therefore, researchers developing MBE technology must be cognizant of the accelerating changes that are taking place in the marketplace. No longer is it possible to develop heterojunction devices and ICs based solely on improved performance (e.g., higher operating frequencies, lower noise figure, higher power output, higher power added efficiencies, wider bandwidths and higher dynamic range). P. Greiling stressed that now, cost-related issues (e.g., growth on larger area substrates, across-wafer uniformity, wafer-to-wafer reproducibility, and reduced cost per wafer growth) must be included in the development of MBE-grown heterojunction device and IC technologies for future system applications.

R.M. Van Buskirk (TRW, USA) described the specific commercial applications of HBT and HEMT components and services at TRW, including examples of end-use products and customers. He attributed the successful growth at TRW ($50,000 in 1991 sales to over $20,000,000 in projected sales for 1996) to their proprietary MBE technology and production capabilities. Key market forces and the prospects for both wireless and wired markets were also highlighted.

Recently there have been strong demands for Hall elements in the field of electronic equipments such as video cassette recorders (VCR), personal computers with floppy disk drives (FDD), and compact disk read-only memory (CD-ROM) drives and other electronic systems. Hall elements are mainly used for brushless motors in those equipments as magnetic sensors. For these applications, Asahi Chemical Industry developed InSb thin film Hall elements having high sensitivity by vacuum deposition. Over 800 million of these InSb Hall elements were produced and served commercially in 1995 which covers 70% of world market. The only problem of the InSb Hall elements is that the operation temperature range is restricted to near room temperature. GaAs Hall elements having wide operation temperature range have been also produced. However, there are still strong demands for Hall element with high sensitivity and wide operation range from low to high temperature for recent application such as current sensors, car sensors, industrial sensors, and so on.

InAs has larger band gap energy than InSb and higher electron mobility than GaAs. Thus, InAs is one of the promising material for Hall element with both high sensitivity and wide operation temperature range as practical magnetic sensors. A Si-doped InAs with 0.5 μm thick grown by MBE on GaAs substrate has high electron mobility of $\sim 100{,}000\ cm^2/V.sec$. By using this InAs thin film, Asahi Chemical Industry developed InAs Hall elements having about 50% higher sensitivity than GaAs Hall element and wider operation temperature range than InSb Hall element. For mass production of this InAs Hall elements, I. Shibasaki and co-workers designed a production MBE system with multi-wafers substrate holder having large growth area (e.g. a substrate holder with twelve 2 inch wafers). After a rather long installation efforts, they found a standard production growth condition for Si-doped InAs thin films. High device yield was obtained for production of InAs Hall elements. The Si-doped InAs Hall elements has excellent properties compared to InSb Hall element such as wide range of operation temperature, moreover stability for pulse voltage noise, low offset drift and low noise properties, all of which are effective for low magnetic field sensing in practical applications. In 1995, 2 million of this InAs Hall element have been applied to DC current sensors, brushless motors, etc., as practical magnetic sensors.

J. Faist (Bell Labs) showed how quantum cascade lasers operating with high powers at room temperature can be fabricated. Maximum peak output powers of about 200

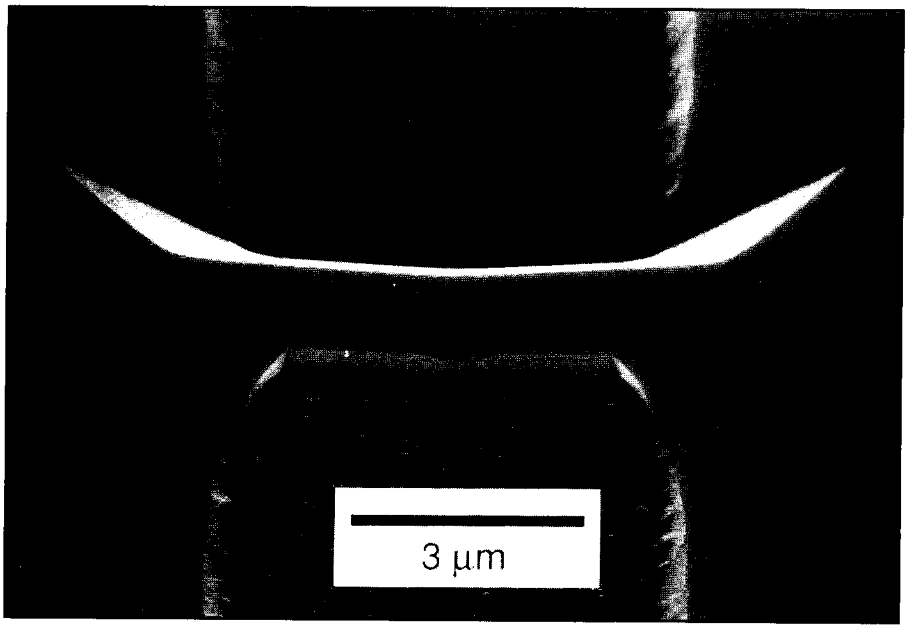


Figure 4: An SEM picture of the wire grown on the pattern with W=0.8 μm and L=3 μm (courtesy of Dr. T. Noda, University of Tokyo, Japan).

mW at 300 K and 100 mW at 320K were obtained. It is claimed that this is the first demonstration of high power, room-temperature operation of any semiconductor source in the mid-infrared (3.5-12 μm wavelength).

## Quantum dots (contributed papers)

The fabrication of low-dimensional structures, such as quantum dots, have been intensively pursued in recent years in order to realize novel devices using confinement effects. In this section I will report only on some of the contributed papers. There were also several interesting posters reporting on this subject.

**Low-threshold (100A/cm$^2$) injection lasers based on vertically coupled InGaAs/GaAs quantum dots**
V.M. Ustinov *et al.*

**Alternating MBE formation of multiple layers of InGaAs quantum dots and application to quantum dot lasers**
R. Mirin *et al.*
University of California, Santa Barbara, USA.

**Self-assembling InP quantum dots for red laser diodes**
K. Eberl *et al.*
Max-Planck-Institut FKF, Stuttgart, Germany.

**Vertical coupling and lateral transport in growth induced InAs quantum dot columns**
G.S. Solomon *et al.*
Stanford University, USA.

**Self assembled structures of closely stacked InAs islands grown on GaAs by molecular beam epitaxy**
Y. Nakata *et al.*
Fujitsu Laboratories Ltd., Japan.

**Room temperature luminescence from self-organized $In_xGa_{1-x}As$/GaAs ($0.3 < x < 0.45$) quantum boxes with high size uniformity**
K. Kamath *et al.*
University of Michigan, Ann Arbor, USA.

**Growth and characterization of self-organized InSb quantum dots and quantum dashes in InP**
T. Utzmeier *et al.*
Inst. de Microelecctrónica de Madrid, Spain.MBE growth of novel GaAs/n-AlGaAs field effect transistor structures with embedded InAs quantum traps and their transport characteristics
G. Yusa and H. Sakaki
University of Tokyo, Japan.

**Selective MBE growth of n-type GaAs wire and dot structures using atomic hydrogen and their electronic properties**
T. Noda *et al.*
University of Tokyo, Japan.

Quantum dot lasers have been predicted to exhibit improved characteristics as compared to quantum well lasers owing to modification of the density of states. Using the concept of vertically coupled quantum dots allowed V.M. Ustinov *et al.* (A.E. Ioffe Institute, Russia) to reduce room temperature threshold current density and to extend the range of current thermal stability up to 160-180K. In this talk, V.M. Ustinov reported on the effects of emitter growth temperature and active layer design on lasing characteristics of quantum dot lasers grown by MBE. It was found that annealing the dots at 700°C results in a marked shift of PL emission toward higher energies. TEM studies showed, that the reason for this is the decrease in In content in a quantum dot, while the dot size is affected only slightly. When the emitters of a GRINSCH laser are grown at 700°C (ie, the quantum dot region is subjected to 700°C for ~1.5 hours), room temperature threshold current density is decreased owing to the improvement of the structural quality of low temperature GaAs covering quantum dots, lasing wavelength shifts due to the In composition reduction in a quantum dot, and the range of current thermal stability is decreased owing to reduction of the carrier localization energy. Increasing the number of quantum dot sheets lead to a dramatic decrease in threshold current density due to improvement of optical confinement factor. The lasing wavelength of lasers based on vertically coupled quantum dots are considerably higher as compared to that of single-sheet dot lasers due to electronic coupling between neighbouring dots. Laser based on 10 sheet vertically coupled quantum dots showed room temperature threshold current density as low as 97 A/cm$^2$($\lambda = 1.05$ μm).

Self-assembling InP quantum dots are prepared by solid source MBE. The dots have a diameter of 15 to 50 nm and a height of 5 to 15 nm depending on the nominally deposited InP layer thickness between 1.5 and 7 monolayers. Transmission electron microscopy and atomic force microscopy studies were presented by K.Eberl *et al.* (Max-Planck Institute, Germany) to provide information about the structural properties. The InP quantum dots are embedded in InGaP lattice matched to the GaAs (100) substrate and show a strong and narrow photoluminescence (PL) at room temperature in the energy range from 1.6 to 1.85 eV. PL measurements on samples with several closely packed layers of dots indicate a degradation of the PL intensity and linewidth for distances below 30 nm between the layers. Laser structures are prepared with one and several layers of InP quantum dots within the 160 nm thick InGaP wave guide region. There are 0.7 μm thick AlInP layers below and above the InGaP wave guide. In optical gain measurements they observed two gain peaks, which were attributed to the wetting layer and the quantum dots. They have also optically pumped cleaved samples with a length of 500 μm. As expected from the results of the gain measurements they observed lasing at room temperature of either the quantum dots or the wetting layer depending on the experimental conditions. Results on electrically pumped laser diodes with one and two layers of dots were also presented.

Islands formed at the initial stage in highly mismatched heteroepitaxy have attracted much interest in device applications. Recently, Y. Nakata *et al.* (Fujitsu, Japan) reported the vertically aligned InAs islands on GaAs stacked with the 10 and 15 nm interval layers. If the upper islands could be stacked closely just on the lower islands with the thin interval layers, the effective island height can be controlled by the stacked layer numbers, keeping the island lateral size and density as those of the first island layer. Y. Nakata *et* *al.* described their recent work on closely stacked InAs island structures grown with 2 and 3 nm interval layers. They stacked InAs islands with the 3 and 2 nm GaAs interval layers by MBE. The growth temperature for the InAs islands was fixed at 510°C and InAs nominal thickness for the island formation was about 1.8 monolayer (ML). Stacked island structures were evaluated by atomic force microscopy (AFM), transmission electron microscopy (TEM) and photoluminescence (PL) measurements. They found that the islands were formed even when stacking with 3 nm intervals. The upper islands expanded gradually with stacked layer numbers. The TEM images of the 5 stacked structures grown with 2 nm intervals indicated that upper islands were grown closely just on the lower islands. The closely stacked structures were almost columnar with about 28 nm diameter and 16 nm height. The broad PL spectrum of the single island layer transformed to be sharp and high-intensity spectra with increasing island layers. The peak energies shifted to the lower energy side. The linewidth of the 5 stacked structure was 27 meV and the peak intensity was about three times higher than that of the single layer structure. These renovated characteristics are useful for the laser applications.

Self-organized InSb quantum dots on semi-insulating InP (001) substrates grown by atomic layer molecular beam epitaxy were reported by T. Utzmeier *et al.* (Institute of Microelectronics, Spain). This system is especially interesting because of the high lattice mismatch of 10.4%. Atomic force microscopy has been used to determine the size-dependency of the uncapped quantum dots on the nominal thickness of the deposited InSb layer. The dot-size showed a pronounced minimum for about 2.2 monolayers (ML) of nominal InSb thickness with a dot-diameter of 24 ± 4nm and a height of 6 ± 3 nm. Above 3.2 ML they observed a drastic change of the dot shape from a point-like to a strikingly elongated one, aligned in the (110) direction. They called the resulting features quantum-dashes. Quantum dots, in general repel each other due to the overlap of their mismatch-induced strain field in the substrate. This repelling force depends quadratically of the dot diameter. In this case of quantum-dashes, their elongated shape causes a highly anisotropic strain-field, that gives rise to higher repulsion in the $(1\bar{1}0)$ than in the (110) direction, as observed experimentally measuring the inter-dash distribution in the two directions, respectively. Photoluminescence (PL) at 12K of the QD samples with and without cap-layer was measured. Both type of samples show PL emission at 1.1 eV and 1.2 eV, respectively, but the emission

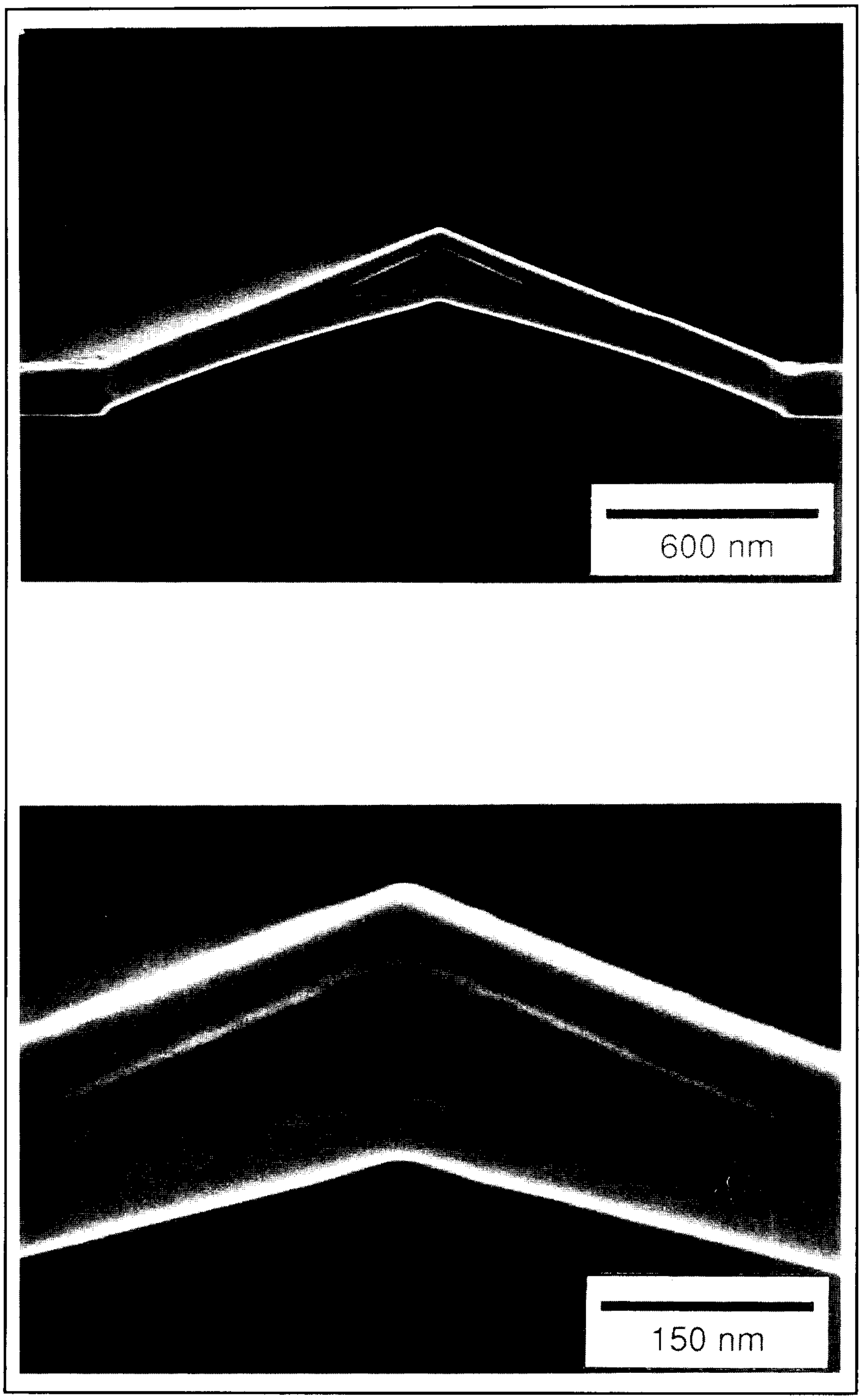

**Figure 5: A cross-sectional SEM picture showing a GaAs quantum dot structure using selective MBE growth (courtesy of Dr. T. Noda, University of Tokyo, Japan).**

energy does not change significantly with the dot-size. This, together with the fact that the PL emission is relatively broad ($\approx$100 meV) and that the quantum dots do not show any signal in photo-absorption measurements indicates a type II band-alignment between the strained InSb and InP. This agrees with theoretical estimations from biaxially strained quantum-wells. Therefore, in the system studied the holes are confined in the InSb, while the electrons are located in the InP.

Fabrication of quantum wires and quantum dots are important, not only for device applications but also for physics of low dimensional systems. Among various methods selective growth of GaAs with $SiN_x$ or $SiO_2$ mask pattern is attractive. Indeed, selective MOCVD and MBE with atomic hydrogens have been used to produce nearly damage-free nanostructures. T. Noda *et al.* (University of Tokyo, Japan) investigated structural features and electronic properties of quantum wires and quantum dots prepared by the selective MBE growth with atomic hydrogens. They grew at 610 ~ 620°C a GaAs layer (0.9 μm), then GaAs/AlGaAs superlattices and selectively-doped 6 nm single quantum wells on (100) GaAs substrates, covered with $SiN_x$ mask patterns. Hydrogen of 0.90 sccm was supplied and the temperature of the cracking cell was ~1600°C. The growth rate was 0.23 μm/hr for GaAs and 0.1 μm/hr for AlAs. The flux ratio $As_4$/Ga was ~6. To fabricate quantum wires, (100) GaAs substrate with a SiNx mask pattern was prepared. The window consists of a narrow constriction (L = 3 ~ μm length and W = 0.8 ~ 4.0 μm width) running along <011> to connect two 50 μm wide regions. By the selective growth of GaAs and quantum well structure, a quantum wire is formed. When they grew a long wire, the diffusion of Ga from the side (111)B plane to the top (100) plane is dominant, resulting in a very sharp ridge structure. In a short wire, however, Ga migrates along the wire and the narrowing of the top (100) plane is strongly hindered. Indeed, spatially resolved photoluminescence (PL) study shows that the thickness of the quantum well in the middle region of the wire is close to 6 nm, suggesting that the material diffusion from the (111)B to the (100) is small. These morphological features indicate the important roles of additional facets formed due to the finite length of the wire. Hence, they have found that the width of the top (100) plane can be squeezed most effectively by employing a long constriction. Using the constriction pattern of 0.8 μm in width, an n-type conductive wire with the geometrical width of 0.3 μm have been formed and the electrons transport have been studied.

By using 2 μm x 2 μm square window along <001> and <010> a quantum dot was formed. MBE growth of GaAs and 6 nm GaAs quantum well was performed at Ts = 620°C. PL of the quantum dot studied at 15 K shows a broad spectrum with a shoulder at 15 meV higher than the main peak. Although the origin of this shoulder is not clear, it is probably due to the electron accumulation in higher levels of the dot.

In conclusion, they have fabricated n-type nanostructures in MBE with the assistance of atomic hydrogens and found that the facets interaction is strongly modified by the presence of additional facets.

## Conclusion

The overall opinion was that despite its enormous size and diversity of scientific contributions, the MBE conference was a worthwhile and very informative meeting.

The social side to this conference was unfortunately not very entertaining due to the lack of meeting places at Pepperdine University which is an alcohol "free-zone" or as some refereed to it as a "dry place". There were, therefore no bar facilities where usually the more serious aspects of line in the crystal growth community are discussed. However, the attenders enjoyed a very entertaining conference dinner.

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duced. To give a fast reading of tray images, a conspicuous X is superimposed on the location of defective IC packages. The system can also automatically mark defective packages with ink.

The system gives semiconductor manufacturers two capabilities they have not had previously: the ability to screen large numbers of IC packages for internal defects quickly, and the ability to uncover defect trends before they become major problems. Pilot production lines – where volume is relatively small and where the goal is to eliminate all process anomalies – appear to be early users of the technology. Manufacturers running low-volume production lines of packages with high intrinsic value are in almost the same position. Both scenarios will be familiar to this readership. But high-speed production lines will probably use the technology as well, because the throughput rate of hundreds or thousands of parts per hour is quick enough to perform a significant sampling of production and thereby give very useful data for achieving parts-per-million failure goals. And failure analysts faced with a storm of defects which must be sorted out from good parts will no longer have to perform miracles of endurance to avoid production shutdowns.

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